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NAVIGATION BY ARTIFICIAL EARTH SATELLITES **/1

H.C.Freiesleben*

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The use of artificial satellites, both variable-orbit and stationary types, for position fixing in sea and air navigation is discussed, with a review of existing system such as the US Transit and Secor satellites. Future projects for navigation over existing ground stations and a world-wide network, using a 24-satellite system, are mentioned briefly. Use of high-orbit satellites with synchronized clocks and interrogation systems is mentioned. Auth

Artificial earth satellites are desirable as navigation aids for position fixing wherever other means fail, i.e., primarily on long distances over oceans or in flights over the polar zones. Over continents, with sufficiently dense population and civilization, air traffic has other means for navigation, which is true also for ships in coastal waters. Above and on the oceans, celestial navigation still remains the most important aid in position fixing. A brief survey over this field readily shows the possibilities of navigation by means of artificial satellites, as well as the basic principles. Measuring the elevation angle h of a celestial body furnishes a correlation between this datum and all pairs of values of latitude φ and longitude λ, for which this value can be observed.

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* Symposium "Data Transmission and Navigation in Cosmic Space", German Association for Rocket Technique and Space Research, April 8, 1965 Munich.

** Numbers in the margin indicate pagination in the original foreign text.

Mathematical-analytically, the formula reads

$$\cos z = \sin h = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos (\lambda - \lambda_o)$$

Geometrically, a circle with the radius z and the center δ, λ_o is in question on the globe. All loci on this circle sight the celestial angle under the elevation h (Fig.1).

If the true locus of a given vehicle is to be defined, from which fixes are taken, two such base lines are required. This is also true for aircraft, since the distance from sea level is so short that it is permissible to assume an area parallel to the earth's surface on which the data for latitude and longitude are defined. The height of the area above sea level must be determined differently.

All position fixes for navigation can be reduced to this basic principle, no matter whether optical or radio aids are involved in the observation or whether one or two objects are in question. The result always is a formula

$$F(\varphi, \lambda, \text{test datum, parameter}) = 0$$

which represents a base line on the globe.

With respect to navigation methods by means of satellites, it is of importance to define what data might be obtainable and what "parameters" will enter the formula. To start with the second item: The formula for celestial /2
position fixing contains coordinates of the celestial body which can be visualized as image point on the earth's surface. In terrestrial objects (radio transmitters, lighthouse towers), their coordinates in latitude and longitude are parameters. This can be no different in satellites. Here again, reference is made to the image point, i.e., the intersection of the connecting line between satellite and earth center with the earth's surface. Whereas this point, in the case of natural celestial bodies, is variable because of the earth's

rotation but still can be calculated in a simple manner (which merely becomes somewhat more complicated in the case of the moon, planets, and sun because of their motion relative to the fixed stars), in the case of satellites their orbital motion must be known. In fact, this motion must be quite accurately defined, and in satellites with a relatively low orbit the time coordinates must be well known.

The locus of the satellite in three-dimensional space is fixed by three parameters. Relative to the observation point, three coordinates are involved which all can be used as test data if they are conceived as polar coordinates, i.e., as two directions (elevation and azimuth) and range. Most satellites move quite near the earth and thus rapidly vary these three coordinates. In contrast to natural celestial bodies, such changes can probably be used as test data.

The direction of a celestial body, in sea and air navigation, is measured relative to a reference direction which, in the case of sea navigation, might be the elevation angle above the visible horizon known also as sea horizon. Optical observations of satellites are unsuitable for purposes of navigation. If natural celestial bodies are available, they will be used preferably. The temptation to use satellites even in such a case could lie in the expected greater measuring accuracy which is offered by an artificial satellite in contrast to natural celestial bodies. However, this accuracy for directional navigation on board ship always depends on the accuracy with which the bearing can be defined. Thus, directional navigation by artificial satellites is well possible, in which case invisible radiation is to be given preference; however, accurate bearings must be established on board. Despite this difficulty, it is hoped that fixes can be taken in the future by means of radio sextants (Fig.2).

Here, a certain facilitation might be obtained by measuring variations in direction rather than the directions themselves, since then an approximate bearing, which is stable over only short time intervals, would be sufficient. /13

In contrast to the four above possibilities, of which none has been used to date, no reference direction and no directional antennas are needed for observation of distances and variations in distance. Already in observations of Sputnik I, it was possible to note the Doppler effect of the rapidly approaching and receding carrier of a transmitter, as well as the difference in the frequency/time curve on transit of the satellite over the horizon of a station on a close or more distant orbit (Fig.3). An American Institute of the University of Baltimore developed the navigation method known as "Transit". The most important characteristic of this method is that the satellite, during one pass over the horizon of the observer who wishes to use the satellite for position fixing, constantly transmits the same frequency and that the observer has a similar constant control frequency available. Both requirements have been met, although - in view of the influence of the ionosphere - only by the artifice of the simultaneous observation of two frequencies, which created the possibility of eliminating, in first approximation, the interfering influence of the ionosphere which falsified the frequency measurement.

In the Transit method, the condition of the base line is somewhat more difficult to define mathematically. Therefore, it should be sufficient to mention here that at least four independent measurements, uniformly distributed in time, must be available while the satellite is above the horizon. In addition to latitude and longitude which must be determined, the local radius vector to the center of the earth must be taken into consideration - the assumption of spherical shape is not sufficient in this method - and the true frequency is entered as an unknown so as to avoid instrument errors. However, the calculations can be so arranged that only the two magnitudes of interest, namely, longitude and latitude, are explicitly obtained. From these statements, it is obvious that such a calculation is more complicated than conventional computations in nautics.

In addition, the basic difficulty of all satellite measurements for position fixing must be recalled, namely, the necessity of an accurate knowledge /4
of the locus of the satellite. Doppler frequencies would be avoided if, for example, a 24-hour satellite were available which would make one revolution about the earth in 24 hrs and thus would remain always over exactly the same meridian. Such a satellite would be excellently suitable for directional navigation, specifically since the evaluation would be extremely simple and no accurate chronometry would be necessary. As a general statement, rapidly moving, i.e., low-orbit satellites, will furnish useful test data for variations in direction or range. However, one difficulty here is the determination of accurate satellite positions. Even if the orbital motion were entirely regular and could be predetermined over long periods of time, the user would need many such basic data and would have to make a careful observation of the instants of time of the measurement, so as to permit an interpolation of the satellite coordinates. Such precalculations are impossible, since the Transit satellites fly so low that their orbits are perturbed in an uncontrollable manner by density fluctuations of the exosphere. For this reason, the inventors of this method equipped the satellite with computer memories which are fed every 12 hrs with new data for position fixing and transmit these in code to the user; because of the continuous-wave transmission, required in view of the Doppler frequency measurements, this latter problem presents no difficulties. Much more difficult

and costly is the required ground organization which is to furnish continuous tracking of the satellites, calculate the orbital data, and transmit these to the satellite (Fig.4). In addition, the work of the observer is made difficult since he is forced to make astronomical computations in order to obtain initial data which then, in turn, are used together with the test data for the relatively complicated position fixing.

The most suitable implement for doing this work is an electronic computer; therefore, it is logical that the inventors of the Transit method thought of the possibility of making more than four observations, for example, one test datum every 6 sec. This permits compensation of an overdetermined system of conditional equations. The results are extremely accurate. Two procedures can be differentiated, of which only the second is useful for on-board use, even in the presence of extensive computer equipment. In addition to taking into consideration the orbital motion in the form of an ellipse whose data are renewed every 12 hrs, it is also possible to consider the perturbations that occur /5
periodically. This is being done by the various tracking stations. With this procedure, the stations were able to derive geoid data from the observation material of the Transit satellite, which are equivalent to the optical test data. On board, one has to be satisfied with the elliptic motion. In 50 observations, it was possible to obtain one position fix with an accuracy to within 150 m, i.e., ten times better than by celestial navigation. Of course, the expenditure is excessive, for which reason NASA finally gave up the search for simplification of this method. In addition, the method has been classified for more than one year now, so that the present status is not known, much to the regret of the inventors.

It is rather logical to think of range measurements with high-orbit satellites, in which the timing and orbital computation is less difficult. In addition, a high-orbit satellite is simultaneously visible over relatively large regions of the earth and thus useful for a navigation method in that it is much more economical. In the case of range finding, the principle used must be that of measuring the transit time of electric signals. The simplest concept is that of two extremely accurate clocks, one of which is housed in the satellite and the other on the vehicle which is to do the ranging. The clock in the satellite would transmit certain signals which are received on board and are compared with the on-board clock. If both clocks are absolutely accurate, the observed time difference will yield the transit time from which, in turn, the range can be determined.

Without such clocks but with an on-board interrogation system in the satellite, a given vehicle on which ranging is to be made would transmit an interrogation signal to the satellite to which the satellite would respond with a reply signal. The time between emission of the interrogation signal and the return of the response pulse would be the double transit time. The Cubic Co. has built the satellite "Secor" for geodetic surveying and has launched it into space. One drawback is the fact that, in this method, a single satellite cannot be simultaneously interrogated by several users since confusion of the signals would take place.

Conversion of the test data into base lines is rather simple; these are circles described about the pertaining image point of the satellite and obtained from the intersection of the earth with a cone whose generatrix is the distance to be measured. Two such circles will then yield the position. If only /6 satellites were available, two successive measurements at a certain time interval would be required, which might impair the accuracy. In addition, the timing and the computational effort would be highly complex. Therefore, NASA developed the brilliant idea of assigning the interrogation of the satellite and the computational work for position fixing to the ground stations which are anyhow in operation for continuous tracking of the satellites. The crew in such stations is best informed as to the instantaneous position of the satellites. In one of the projects, it is now hoped to do the entire work with six ground stations, which are located in the zone of action of at least two satellites and thus are able to supply a certain ground district with data (Fig.5). Simultaneous observation of two satellites has not only the great advantage of direct position fixing but also of more uniform accuracy ratios. One of the projects schedules 24 satellites with an orbit of about 10,000 km, which would yield a fairly complete coverage of the earth (Fig.6).

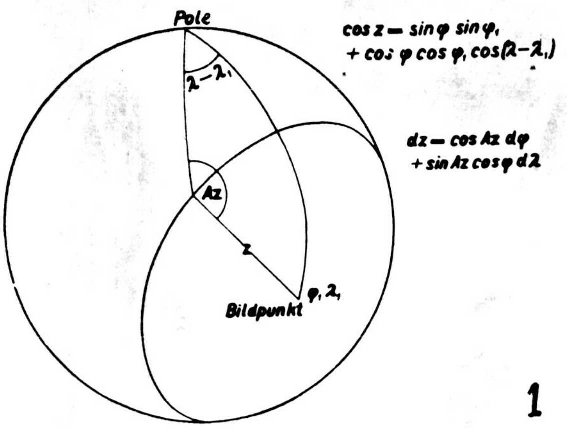
In such a method, the position fixing would proceed as follows: The user reports to the nearest ground station that he desires to obtain a fix with artificial satellites. At a certain, very short time interval, the ground station will transmit pulses in succession to two satellites above the horizon of the vehicle, which are then retransmitted by the satellites to the vehicle in question. On board this vehicle, without participation of the crew, the pulses are picked up by a relatively simple and cheap interrogator which returns a reply to the satellite where it is received and repeated. The ground station receives the pulses twice: The first time when transmitted from the satellite and the second time when repeated by the satellite. The interval of time is the double transit time from satellite to vehicle. The ground station, using two such measurements, computes the position of the vehicle in question and transmits the result to there.

This method makes the ground stations do all the work; however, this is also the case in the Transit method except that now the ground stations also have the function of surveillance of the communication between the various vehicles within their radius of action. This obviously yields an excellent possibility of ensuring air safety control over the entire oceans, which up to now had been rather spotty. Today, the only means of keeping the necessary safe distances is navigation by aircraft. In the case of an airplane crash /7 it is difficult to define the accurate location of the aircraft. This situation could be greatly improved and a closer deployment of aircraft made possible by the new method. A certain military drawback might be the fact that the interrogating vehicle reveals its own position; for this reason, one variant provides for a transit-time difference method in which two satellites synchronously transmit pulses, which is done by proper control from the ground. This makes these satellites foci of a family of two-sheet hyperboloids which, on earth, yield hyperboloid lines as base lines. The main disadvantage of this method is the fact that the highly complicated work-up of the data must be done by the crew.

It is not surprising that only one of the three firms has submitted this particular variant; the others offered no such proposal. However, one of these provided not only for ranging but also for directional navigation over artificial satellites. For this purpose, the satellite is equipped with antennas which permit measurements in accordance with the minitrack method (Fig.7). The frequently mentioned difficulty of reference direction is solved in this manner. The position of satellites with respect to the earth's surface, for various purposes, has been extensively and satisfactorily stabilized. However, for directional navigation, the accuracy must be still greater. It is a fact that the satellites are constantly tracked by ground stations which can thus have the satellite determine their own direction to the satellite. The result will give data on the corresponding location of the antennas in space, which can then be introduced into the position fixing process.

This latter method permits simultaneous measurements with a single satellite which latter, theoretically, even provides three simultaneous test data and thus gives a possibility of determining the height of a given aircraft above sea level as the third unknown. For this reason, this particular project schedules a much smaller number of satellites, just sufficient to have one satellite everywhere above the horizon at all times for position fixing (Fig.8).

In any case, these projects promise a more general usefulness and thus /8
greater economy. One more point in favor is the fact that the improved air safety control offers possibilities of a much closer spacing of transoceanic air traffic. It can be expected that practical experiments will be started in the very near future. This specifically concerns an expansion for the Secor satellites, which are already in orbit.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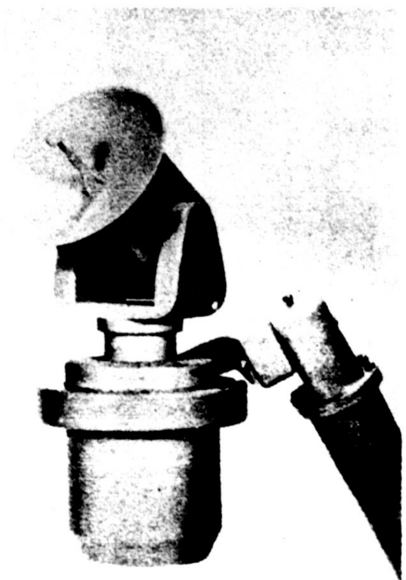

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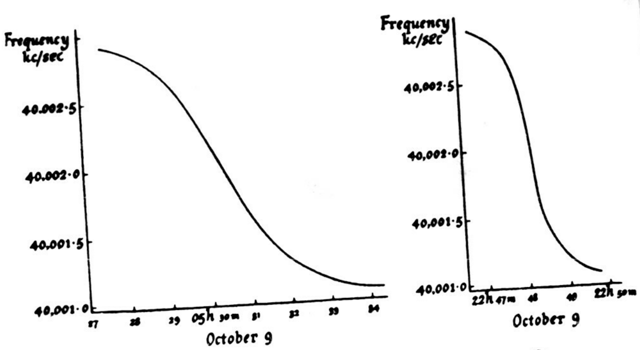
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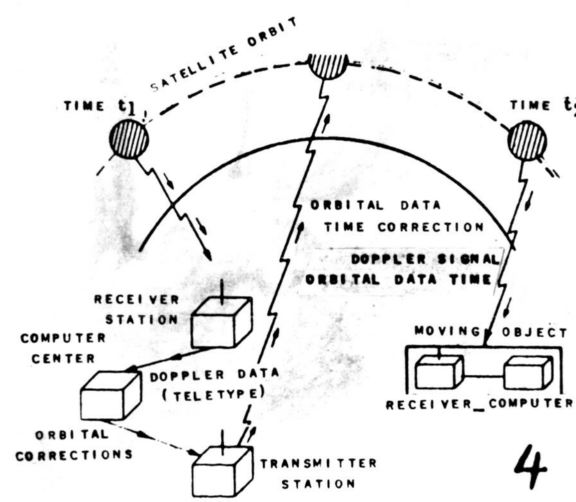
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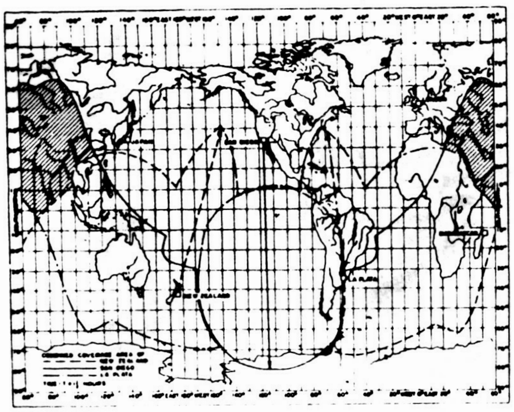

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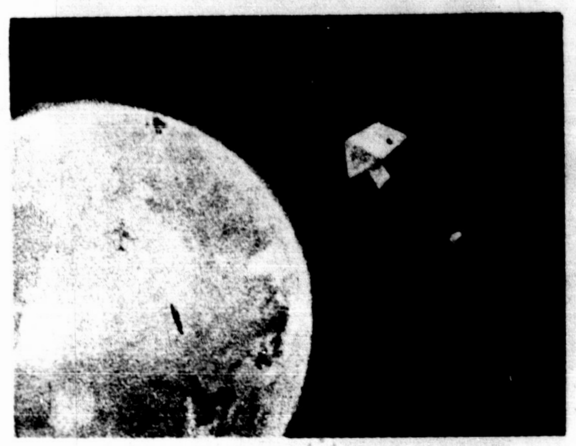

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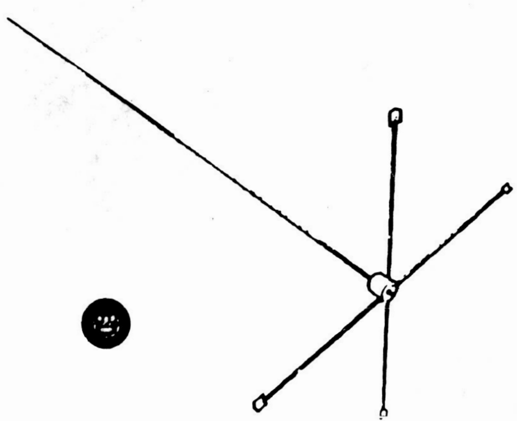

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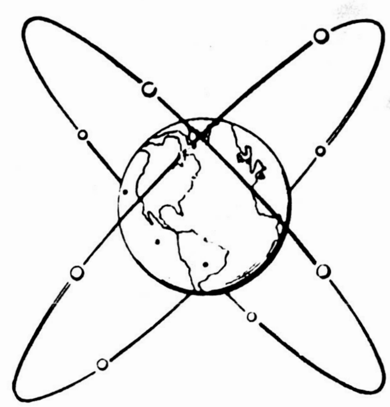

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